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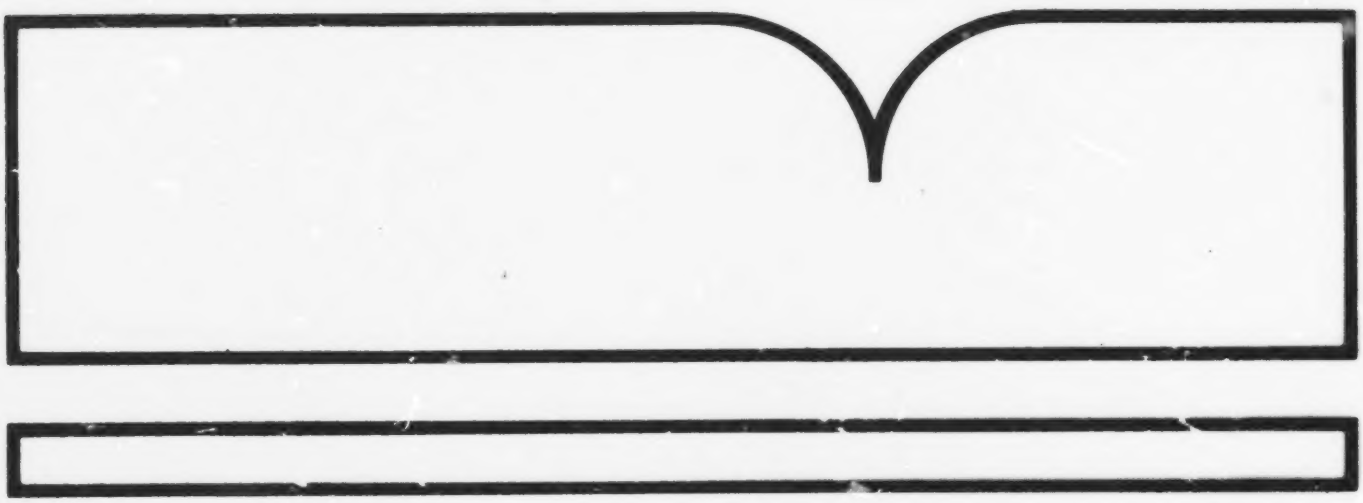

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A long-term program to monitor aquatic ecosystems requires a long-term commitment of significant resources. To maximize the effectiveness of such a program, monitoring sites must be carefully selected, addressing a complex array of relevant concerns in the process. Monitoring sites for the TIME Project (Temporally Integrated Monitoring of Ecosystems), scheduled to begin in 1991, will be selected for chemical and biological sampling in order to meet several distinct objectives including 1) establishing an "early warning" network to detect changes in aquatic resource acidification or recovery, 2) providing periodic regional assessments of surface water acidification status, 3) providing data for validation of watershed models, and 4) relating surface water responses to atmospheric deposition. This paper focuses on a method for selecting sites to meet the first objective for lakes and does so using data from the National Surface Water Survey (NSWS). The approach involves a cluster analysis to stratify the NSWS sample and ordination to identify lakes that are likely to respond to changes in acid inputs.

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SITE SELECTION PROCEDURES FOR TEMPORALLY INTEGRATED MONITORING OF ECOSYSTEMS (TIME)*

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SITE SELECTION PROCEDURES FOR TEMPORALLY INTEGRATED MONITORING OF ECOSYSTEMS (TIME)

Thomas C. Young and Jesse Ford

ABSTRACT

A long-term program to monitor aquatic ecosystems requires a long-term commitment of significant resources. To maximize the effectivess of such a program, monitoring sites must be carefully selected, addressing a complex array of relevant concerns in the process. Monitoring sites for the TIME Project (Temporally Integrated Monitoring of Ecosystems), scheduled to begin in 1991, will be selected for chemical and biological sampling in order to meet several distinct objectives, including (1) establishing an "early warning" network to detect changes in aquatic resource acidification or recovery, (2) providing periodic regional assessments of surface water acidification status, (3) providing data for validation of watershed models, and (4) relating surface water responses to atmospheric deposition. This paper focuses on a method for selecting sites to meet the first objective for lakes and does so using data from the National Surface Water Survey (NSWS). The approach involves a cluster analysis to stratify the NSWS sample and ordination to identify lakes that are likely to respond to changes in acid inputs.

BACKGROUND AND ISSUES

The most extensive information on the current status of surface water acidification in the United States derives from recently completed efforts by the U.S. Environmental Protection Agency (EPA). Under the aegis of the National Acid Precipitation Assessment Program (NAPAP), EPA conducted the National Surface Water Survey (NSWS) during the mid-1980's. This program included the National Lake Survey (NLS) and the National Stream Survey (NSS). The results of these efforts have been reported in detail (Linthurst et al. 1986, Landers et al. 1987, Kaufmann et al. 1988). It is clear from these surveys that poorly buffered surface waters occur widely and that systems located in regions of high acidic deposition evidence the greatest degree of acidification (Landers 1988, Eilers 1988).

Among existing water quality monitoring programs, few have combined regional and temporal design elements in a manner that is adequate to determine the effects of declining emissions on aquatic systems, and none have been designed specifically to meet that objective. The EPA's Long-Term Monitoring Project (LTMP), a major effort that pertains to lake ecosystems likely to respond to deposition changes, incorporates some spatial and temporal analysis (Newell et al. 1987, Ford et al. in prep.). LTMP involves seasonal to monthly sampling and analysis for acidic deposition effects on nearly 100 lakes in the northeastern, midwestern, and western United States. LTMP lakes were not selected randomly, however, so they do not represent explicit regional lake populations or subsets, in contrast with the NSWS lakes (Blick et al. 1988; Pollack and Ford, this issue). As a consequence, changes in water quality status and trends observed in LTMP lakes cannot be interpreted without bias as representing the average response of the regions in which they are located.

EPA's TIME Project (Temporally Integrated Monitoring of Ecosystems) seeks to bridge the design gap that exists between the NSWS and the LTMP projects and, in so doing, provide the information needed to assess the effectiveness of emissions controls on acid-sensitive aquatic systems. By building on experience gained during the NSWS and LTMP efforts, the TIME Project will integrate spatial with temporal monitoring. In the introductory paper to this symposium session

on the TIME Project, Pollack and Ford (this issue) describe the goals of the TIME Project. This paper provides an overview of the process that will be used to guide selection of monitoring sites as the first step in achievement of these goals. While the TIME Project includes monitoring of streams as well as lakes, the focus of this paper will be on the selection of lake systems. A combined total of approximately 200 lakes and streams are planned for inclusion in the nationwide monitoring program.

APPROACH

The main goals of the TIME Project have been given by Thornton et al. (1987) and also by Pollack and Ford (this issue). The goals also have been stated as specific project objectives (Thornton et al. 1987). These objectives are restated here to give a point of focus for discussing site selection procedures. The objectives of TIME are to:

1. Provide early detection of changes in surface water acidification in regions of interest.
2. Provide periodic assessments of regional patterns and trends in surface water acidification status.
3. Determine the degree to which chemical and biological patterns and trends correlate between surface waters observations and watershed model forecasts.
4. Determine the degree to which chemical and biological patterns and trends correlate between surface waters and atmospheric deposition.

Objective 1

The first project objective will require monitored sites that provide early detection of changes in acid-base chemistry. Such systems must be highly responsive to acidic loadings to minimize the time required to detect trends and changes in acid-base status.

A significant obstacle to selecting monitoring sites that are especially sensitive to acid and base loading is the need to define aquatic system characteristics that will permit early detection of

change by satisfactory monitoring procedures. This difficulty is discussed more fully in a later section, but an example is useful here. A measurement of water column pH gives a direct indication of free acidity in an aquatic system, so a superficial view might conclude that pH would serve well as an indicator of sensitive systems for TIME Project monitoring. Water column pH, however, may be relatively stable at high or low values depending on the buffering provided by other aqueous chemical components. Consequently, water column pH provides an ambiguous criterion for ranking lake sensitivity to acid and base inputs. To make the example more specific, pH in very low ANC (acid neutralizing capacity) systems may be buffered by aluminum hydrolysis or humic substance protolysis. The pH in aquatic systems with these attributes would be low but comparatively unresponsive to changes in acid or base inputs. Thus, robustness of the selected parameter for defining sensitivity is important. Furthermore, the parameter should be measureable with relatively high simplicity, precision, and accuracy to measure to increase the likelihood of its presence in datasets of interest.

The lake and stream populations that formed the basis for NSWS site selection will comprise the main populations of interest to the TIME Project, with the addition of sites from the Kenai Penninsula in Alaska. Lakes from the latter region will be added because they are similar in many characteristics to lakes of the upper midwestern United States, but they occur in a region significantly less affected by acidic deposition (Ford et al. 1988, Landers et al. 1989). The known statistical attributes of these populations make the NSWS/Kenai sites particularly desirable for some purposes (see Objective 2). Nonetheless, non-NSWS monitoring sites ("found" sites, Overton 1989), also will be considered for selection if the data collected to date are especially relevant and of high quality.

It may be neither possible nor necessarily desirable to select monitoring sites solely and randomly from NSWS/Kenai lake groups (strata) formed on the basis of early detection criteria. Such a constraint on site selection would be necessary to yield unbiased estimates of change in lakes within large geographic regions (Objective 2). However, randomly selected sites may not be efficient at guaranteeing inclusion of lakes that are most sensitive and, therefore, best able to

provide early warning of change. Rather, a purposive ("hand-picked") sample may be most useful for early detection of deposition-related changes in water quality, depending on (1) the number of lakes from which sites may be selected, (2) the number of lakes upon which projections are to be cast, and (3) how much prior information is available on the lakes.

Objective 2

In contrast with the possible use of nonrandomly selected sites for meeting the first objective, determining temporal changes in surface water acidification for large geographical regions will require randomly selected sites from the region of interest. Statistical population frames (enumerated lists of all possible sampled sites) for both streams and lakes in regions of high suspected effect from or sensitivity to acidic depositiion were developed for the NSWS. These frames will be used for site selection by the TIME Project.

It is expected that the selection process for lakes will follow an approach similar to that used to estimate temporal changes in acidification in the northeastern United States during the NSWS (Phase II of NLS; Thornton et al. 1986, Overton 1987). In order to implement this approach, known as double sampling (Cochran 1977, Overton 1987), the sample of lakes selected for regional lake status characterization (Phase I of NLS) will be restratified based on sensitivity and response parameters developed to select early detection sites for Objective 1. Subsequent to restratification, a suitably-sized, random sample of sites will be drawn and reweighted for parameter estimation as required by the Phase I and restratified sample characteristics (Overton 1987).

Objective 3

The third objective requires monitoring of sites that have been included in EPA's forecast modeling efforts. Of particular interest are the lakes (a random subsample of the NLS Phase II lakes) that formed the target systems for EPA's essentially completed Direct-Delayed Response Project (DDRP, Church et al. 1989). DDRP is an extensive catchment-receiving water characterization and modeling project focused on the northeastern and southeastern United States

Although the DDRP will not achieve formal completion until 1990, much of the modeling activity has concluded (Church et al. 1989). Accordingly, modeling forecasts of water quality sensitivity and response to a range of future acidic deposition scenarios, ranging from a few years to several decades, are available for all included systems. Consequently, TIME monitoring sites selected from DDRP lakes can include systems for which forecasts indicate early response, as required to meet Objective 1. Selection specifically on the basis of forecast characteristics, however, eliminates the element of randomization from the selection and precludes the use of such lakes for regional acidification estimates.

Objective 4

Assessment of relationships between trends in surface water response and deposition chemistry ideally requires surface water monitoring sites in proximity to deposition monitoring sites. Purposive selection of early warning sites, a protocol likely to be used for a fraction of TIME monitoring sites, can also ensure some degree of achievement of the proximity requirement. But, as discussed by Daly (this issue), a major issue facing the TIME Project is the adequacy of existing monitoring networks (e.g., the National Atmospheric Deposition Program/National Trends Network) for providing sufficiently accurate deposition data for meeting Objective 4. If existing networks should prove to be inadequate, the TIME Project will recommend installation of additional deposition monitoring sites and provide recommendations on site locations.

In summary, the TIME Project will use water quality monitoring sites that include both randomly and purposively selected systems. Sites chosen randomly from the NSWS sampling frame, after restratification, will enable estimation of regional response to deposition in terms of chemical and biological trends and changes in status through time. On the other hand, early detection of changes in surface water acidification, assessment of model predictions, and determination of relationships between surface water response and deposition chemistry have need of sites selected with prior knowledge of candidate systems chemical and biological characteristics.

SPECIAL CONCERNS IN SITE SELECTION

Inclusion and Exclusion

In addition to factors derived directly from primary project objectives, other factors that indirectly relate to the objectives (Table 1) also affect site selection. Some of these factors will be addressed within the TIME Project by applying formal rules for inclusion and exclusion of candidate monitoring sites. Although these rules are not addressed explicitly here, published descriptions of site selection protocols for the NSWS (Linthurst et al. 1986, Landers et al. 1987, Kaufmann et al. 1988) provide entirely relevant examples of criteria that would apply to selection of TIME monitoring sites.

A special concern on the list given in Table 1 is that of watershed disturbance. The TIME Project specifically addresses questions related to changes in water quality attributable to changes in acidic deposition. As a consequence, uncontrollable, confounding influences on water quality, as would accompany human activities in a watershed, should be avoided or at least minimized to the extent possible.

"Found" Monitoring Sites

In the preceding discussion of project objectives and site selection, several issues were identified that have particular importance to the TIME Project. One is the problem of whether and how to make regional population estimates using data from monitoring sites selected in part by exercising a probability protocol, such as, random sampling from an explicit frame, and in part by a nonprobability selection, such as, picking sites in a region on the basis of length of pre-existing record.

Often the difficulty of monitoring sites selected by a nonprobability procedure is compounded by a lack of recognition that a problem exists in data interpretation. A simple example will illustrate the nature of the situation. Given a monitoring program for a region based on a random sample of 20 lakes, why should ANC data available from a local researcher on a particular lake in the region (not part of the random sample) be excluded from estimates of the regional mean lake ANC? Perhaps it should not. Generally speaking, however, the local researcher's reasons for picking the

Table 1. Ancillary factors affecting site selection for the TIME project.

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* Watershed disturbance
  - Road salt from deicing activity
  - Chemical manipulation (e.g., limestone neutralization)
  - Land use (agriculture, habitation, transportation, and others)
* Length and quality of pre-existing chemical record
* Intensive or extensive monitoring effort at site
* Suitability for both chemical and biological monitoring
* Flexibility for meeting future changes in research focus or level of activity
* Likelihood that region will experience a significant change in deposition
* Accessibility for sampling
* Regional heterogeneity or presence of spatial gradients
* Special conditions and value of data if site was selected by a nonprobability protocol
  - Lake or watershed area
  - Soil type
  - Hydrologic regime
  - Indirectly related research interest

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site will not duplicate those of the regional monitoring program. Thus, the primary obstacle to including the local researcher's information is a lack of knowledge about the "representativeness" of the lake for estimating the regional chemistry. The representativeness of the random sample, on the other hand, is not in doubt if selected according to protocol.

As explored by Overton (1989), statistically rigorous procedures can be developed that permit "found sample" inclusion on the basis of an informed judgement on representativeness. These procedures, however, will require more testing before their general usefulness can be established.

Early Detection and Restratification Criteria

An essential issue for the TIME Project is the identification of aquatic system characteristics that permit early detection of acid-base status changes and that may be monitored satisfactorily. One approach to identification of suitable characteristics, and the one followed here, is to consider information that reflects the sensitivity and past response of candidate systems to acidic deposition. Given the identification of suitable water quality characteristics, relevant data on the candidate sites will allow their classification into sampling strata. Subsequently, sites may be randomly selected from one or more strata for inclusion in the monitoring program, subject to application of the exclusion criteria mentioned previously.

The NSWS database contains a wealth of information related to the acid-base chemistry of lakes and streams that may be used to characterize the sensitivity and response of those systems and their potential usefulness for early detection of change in status. One view of a small subset of the available information is shown in Figure 1, which illustrates the relationship between bicarbonate ion and divalent cation concentrations in drainage lakes in Regions 1 (Northeast) and 4 (West) of the NLS. Regions 2 (Upper Midwest) and 3 (Southeast) were not included on Figure 1 to reduce data density for plotting. These data indicate the existence of a strong linear association (approx. 1:1, equivalent basis) between these quantities in a majority of lakes, particularly in Region 4. Also, a strong divergence from this pattern was evident, mainly in lakes from Region 1. The divergence is consistent with the pattern expected from a catchment-receiving water system wherein strong acid

Drainage Lakes of the National Lake Survey
Regions 1 (Northeast) and 4 (West)

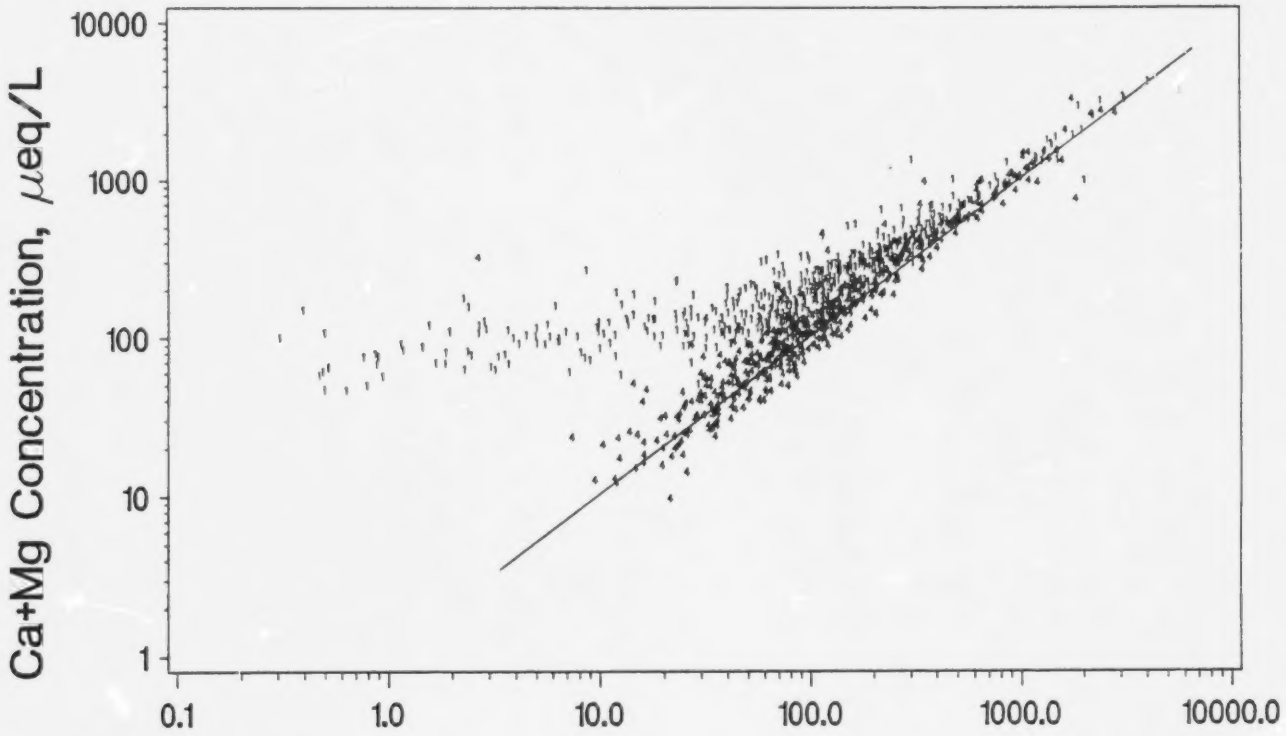

Figure 1

anions, such as sulfate or nitrate, or organic ligands have replaced bicarbonate in the electroneutrality balance.

Based on the assumption that divalent base cations, particularly Ca, and bicarbonate ion generally share geochemical origins (the weathering of carbonate bearing minerals), these data suggest the occurrence of lake response to acid inputs. Clearly, precipitation sources of acids cannot be distinguished from natural sources from these data, but the geographical distribution of the apparent ion replacement (Northeast > West) is consistent with that of precipitation sources of acids (Husar 1986). The lowest concentrations of bicarbonate occurred in lakes that contained comparatively high divalent cation levels. Hence, considering the entire NLS results, the lakes with the greatest apparent response to acid inputs (least bicarbonate relative to divalent cation levels) formed a separate group from those with the greatest apparent sensitivity to acid inputs (least bicarbonate present in amounts equivalent to divalent cation concentrations). Based on this characterization scheme, it appears that lakes in the northeast include most of the high response systems, while high sensitivity lakes (divalent cations equivalent to bicarbonate ion concentrations, low concentrations) comprise the majority of systems in the west.

Sensitivity and response inferences such as these will be used in the process of selecting TIME monitoring sites. The nearly 1100 member drainage lake subsample from NSWS Regions 1 and 4, depicted in Figure 1, can facilitate a simple demonstration of the workings of a strategy that uses sensitivity and response information. This data subset, of course, neither includes lakes from all United States regions of interest regarding acidic deposition, nor considers hydrologic types other than drainage lakes.

Drainage lakes may be partitioned objectively into a number of subgroups, or clusters by applying a classification algorithm to individual lake characteristics contained in the NSWS database. The lake characteristics selected for clustering may include, but need not be limited to, variables selected to quantify sensitivity and response. Including a variety of limnological variables in the cluster analysis, rather than just those that reflect sensitivity or response to acidic deposition, results in clusters that more broadly define lake subpopulations present in the NSWS sample. Such a

multivariate clustering, however, will have less power to discriminate between sensitive and responsive lake classes, compared to clustering, for example, on ANC alone. This develops because the multivariate strategy uses additional variables to define lake categories, and the additional dimensions of variance decrease distinctions among clusters.

After lake clusters are formed, those that rank highly on the sensitivity and response variables may be subsampled, randomly if desired, to provide a selection of monitoring sites that may be considered representative of the sensitive or high response lakes. The number of lakes desired for monitoring may exceed the number available in a single cluster, so selection of more than one cluster may be needed to fill the sample. In this case, the most sensitive or highest response cluster may be censused if desired, or the subsampling process may be extended to multiple clusters to provide broader representation of lake classes in the monitoring program.

The lakes represented in Figure 1 were partitioned into eight subgroups by a nonparametric cluster analysis (Two-Stage, Kth Nearest Neighbor Density Algorithm; SAS Institute, Cary, NC) using log-transformed lake concentration data for total alkalinity, dissolved organic carbon (DOC), and the ions: chloride, hydrogen, and sulfate. The results of the analysis are summarized in Figure 2, wherein circles identify the position of lake clusters. The center of each circle marks the cluster mean for divalent cations and bicarbonate ion, and each circle diameter is proportional to the number of lakes in the cluster (cluster membership). The multiple-member clusters are identified by letter; the largest of these has 266 lakes while the smallest has 18. Single-member clusters (54 occurred) are represented by the very small open circles scattered around the other clusters and are regarded as relatively atypical or unique chemically. These relatively rare lake types can be aggregated into the existing clusters for completeness, if desired, but the resulting clusters lose compactness.

The nature of the clusters plotted in Figure 2 may be described from intracluster averages of the clustering variables. Based on the earlier discussion of the sensitivity and response of lake waters to acid and base addition, three clusters of high interest for TIME Project monitoring include Clusters B (Membership=N=166), D (N=18), and G (N=33). The other clusters also are likely to be

Non-Parametric Clustering of Drainage Lakes
National Lake Survey Regions 1 and 4

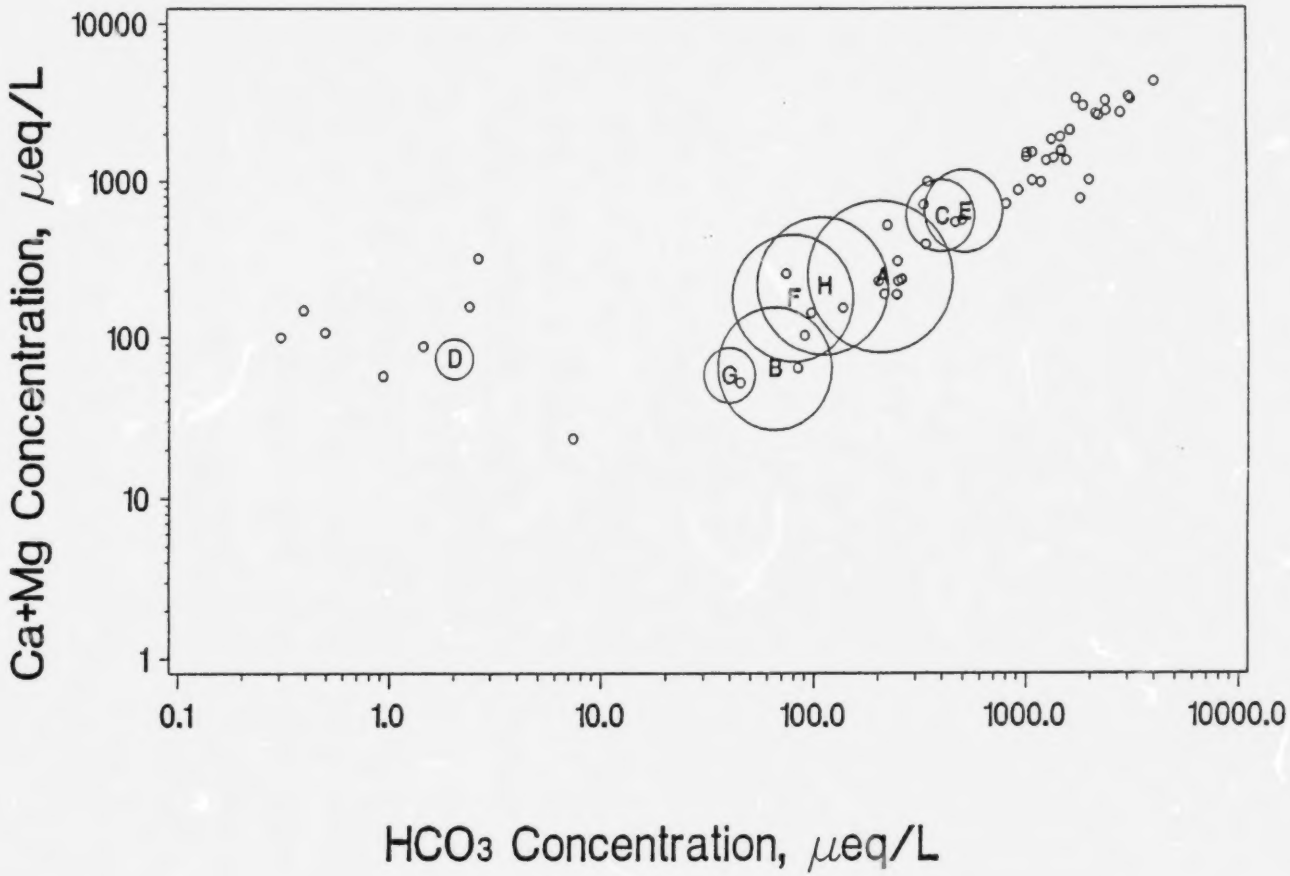

Figure 2

of interest to ensure representation of major lake types or for other reasons. For illustrating the approach, however, this discussion will focus on Clusters B, D, and G.

The three clusters of interest contain lakes with very similar concentrations of divalent cations (Ca + Mg); however, they are dissimilar in several other respects. As seen in Figure 2, Cluster D lakes were markedly reduced in bicarbonate ion, compared to Clusters B and C. Further, lakes in Cluster D had an arithmetic mean pH of 4.82, compared with 6.85 and 6.75 in Clusters B and G, respectively. Organic acids influenced these differing levels of acidity, as average DOC in Cluster D (4.7 mg/L) exceeded that of Clusters B and G by three- and tenfold, respectively. Much of the acidity difference, however, was due to elevated mean sulfate ion concentration in the highly acidic Cluster D lakes (113.4 ueq/L). Clusters B and G averaged 6.2 and 19.5 ueq/L for this parameter. From these comparisons, it seems reasonable to suspect that the Cluster D lakes, all of which are situated in the northeastern United States, have experienced significant replacement of bicarbonate by sulfate ions, possibly attributable to atmospheric sources.

Cluster D lakes averaged approximately twofold greater conductivity levels compared to those in the other two clusters (23.6 versus 8.3 and 9.5 uS). This difference, however, was due largely to high concentrations of sulfate ion and extractable Al (165.1 ug/L versus 5.8 and 4.4 ug/L) in the highly acidic Cluster D lakes, rather than to road salt contamination or other watershed disturbance. Chloride levels in lakes of the three clusters were very low, and averaged less than 15 ueq/L, which suggests little direct watershed disturbance in these lakes.

The largest contrast between lakes in Clusters B and G occurred with sulfate and nitrate ion concentrations. Lakes in Cluster G contained mean sulfate and nitrate ion concentrations of 19.5 and 4.0 ueq/L compared with 6.2 and 0.9 ueq/L for Cluster B lakes. Inasmuch as both Cluster B and Cluster G lakes were located exclusively in the western United States and both contained lakes from all western subregions, these differences may not be attributable to regionally distinct patterns in SO4 deposition.

To draw a sample of lakes for monitoring from these clusters, cluster membership can be treated as a class variable, and a stratified sample may be selected, randomly if desired. Allocation

of samples among the clusters may be arbitrary, equal, proportional, or dependent on attribute or cluster variances. The choice of allocation strategies also will depend on available resources, or desired total sample size and the kinds of estimates required of the sample data.

SUMMARY

The TIME Project requires water quality monitoring in lakes and streams to allow (1) early detection of aquatic ecosystem responses to acidic deposition, (2) assessment of regional patterns and trends in surface water acidity status, (3) verification of watershed model forecasts of water quality response to atmospheric deposition, and (4) evaluation of the correlation between surface water quality and atmospheric deposition. To achieve these objectives, various monitoring site selection approaches will be required. This paper has touched on several and explored one approach that makes use of data from lakes sampled during the NLS. The method provides a sample of lakes that is appropriate to the objective of early detection of ecosystem response.

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LIST OF FIGURES

Figure 1. Relationship between equivalent concentrations of major divalent base cations and bicarbonate anion in drainage lakes of the northeast and western United States; straight line has 1:1 slope; data from National Surface Water Survey (Linthurst et al. 1986, Landers et al. 1987).

Figure 2. Ordination of drainage lake clusters on base cation --bicarbonate anion concentration axes; clusters formed from lakes shown in Figure 1.